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POTHOLES: THEIR VARIETY, ORIGIN AND SIGNIFICANCE. II.

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INITIATION AND DEVELOPMENT OF NORMAL POTHOLES

IT is evident from the classification given above that all varieties of pothole depressions have a turning or vortex flow of water (provided with sediment tools) as at least a contributing factor in their formation. Accordingly, it would seem that an investigation of the exact conditions of the initiation and development of the normal type of pothole would furnish the most significant data in regard to the origin of these depressions in general, and also furnish some measure of their function in the process of gorge cutting by young streams. Some results of such a study and deductions based on actual observations with particular reference to occurrences in horizontally bedded sandstones and shales follow.

Ideal Normal Potholes.—Normal potholes are developed by the rotary grinding motion imparted to rock tools—sand, pebbles, boulders—in a depression of the bed of a stream course by the water current. A typical normal pothole should have the following characteristics: At the top the hole should be almost circular in ground plan, with a diameter ranging from three inches to ten feet or more. The depth might vary between six inches and eight feet or more. In vertical section an ideal normal pothole should show the same outline as that of a similar section through one of the old-fashioned iron pots that have wide curved mouths and bulging sides (see Fig. 8). No doubt normal potholes owe their name to this resemblance. There are, however, many deviations from this perfect form. The holes show much irregularity in ground plan as well as lack of symmetry in the bulging of the sides. Very commonly the smooth inside surfaces of the excavations are interrupted by ridges or flutings. Other typical examples of normal potholes are shown in Figs. 9*a*, 9*b*, 10. The kinds of material that may be found in the potholes are of interesting variety. Usually masses of rubbish consisting primarily of sand, gravel, pebbles and boulders and perhaps fragments of other materials are found in holes either temporarily or permanently abandoned by the stream. Some of the pebbles or boulders may be smoothed and rounded, due to the grinding action. In describing the material taken from some potholes in Norway, Brögger and Reusch[25] state that two types of grinding stones may be distinguished: (1) Perfect or regularly elliptical; (2) less perfect with elliptical tendency. According to these writers the perfect type of grinding stones become more numerous near the bottom of the hole. The grinding stones are usually of the harder, more resistant kinds of rock such as sandstone, quartzite, etc. Due to their almost spherical or elliptical form the grinding stones often attract much attention and in not a few cases such beautifully rounded stones have been gathered as curiosities or for use in rockeries.

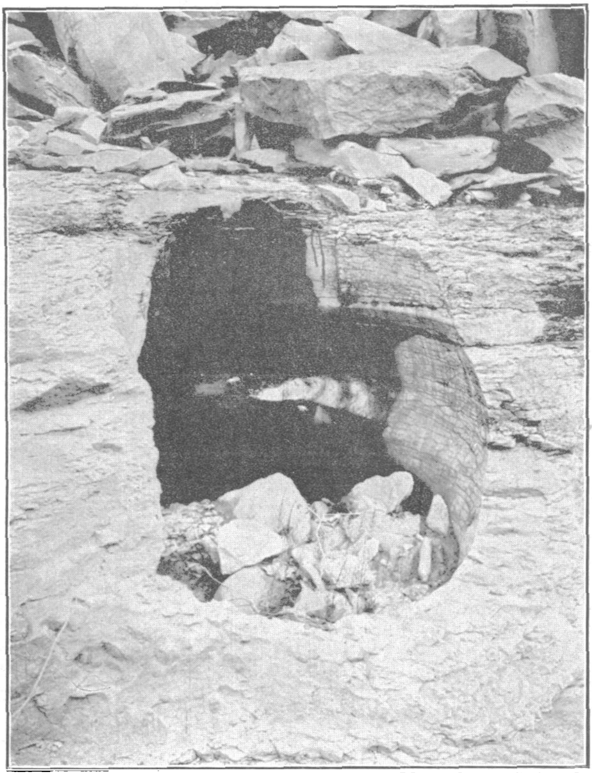

Photo by J. S. Hook.

FIG. 8. SECTION OF NORMAL POTHOLE, showing similarity in shape to old-fashioned iron pot. Note ridges or flutings on interior surface.

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[25] Brögger, W. C., and Reusch, H. H., "Giants' Kettles at Christiania," *Quart. Jour. Geol. Soc. of London*, Vol. 30, pp. 754–761, 1874.

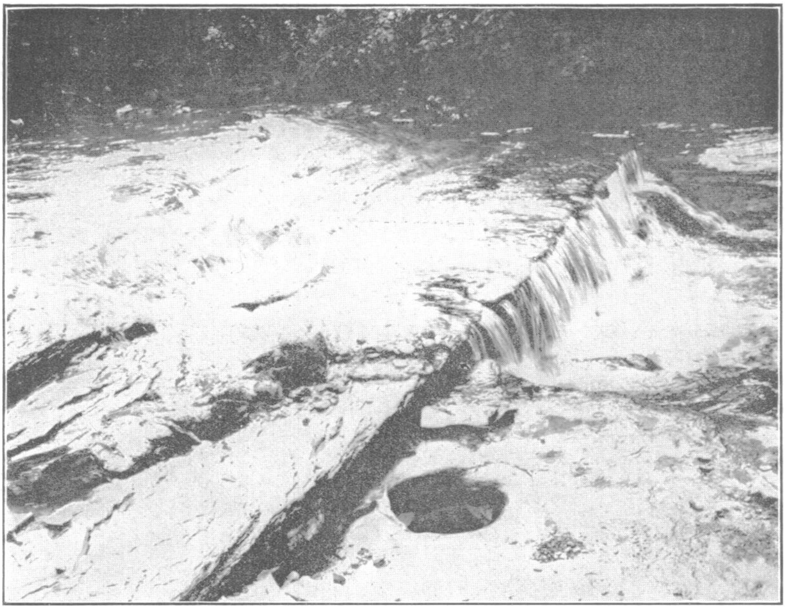

FIG. 9A. NORMAL POTHOLE IN UPPER GORGE OF CASCADILLA CREEK, ITHACA, N. Y.

During periods of high water, sand, gravel and boulders are swirled by the current and become very effective as abrasive agents both in smoothing, rounding out and enlarging the hole and also in reducing to finer fragments the tools themselves by rubbing them against each other and rounding the pebbles.

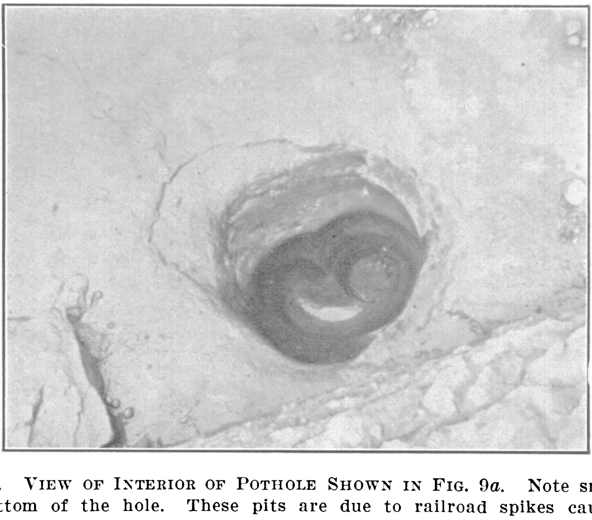

FIG. 9B. VIEW OF INTERIOR OF POTHOLE SHOWN IN FIG. *9a.* Note small pits at right in bottom of the hole. These pits are due to railroad spikes caught in the pothole and then hammered repeatedly against the sides by the water current and fragments of rock.

When the erosive action ceases the holes are choked with this detritus, the greater part of which is sand and silt. In some cases, however, much of the material is rock fragments of the size of gravel or even of larger pebbles. The material in an abandoned pothole very commonly is packed in so closely that much effort is required to pry out the fragments. A pothole in the Ithaca region, so packed, contained, in addition to a considerable amount of sand and gravel, several railroad spikes which had been used as tools in the excavating process for the points of the spikes had been firmly driven and wedged into niches in the bedrock (see Fig. 9).

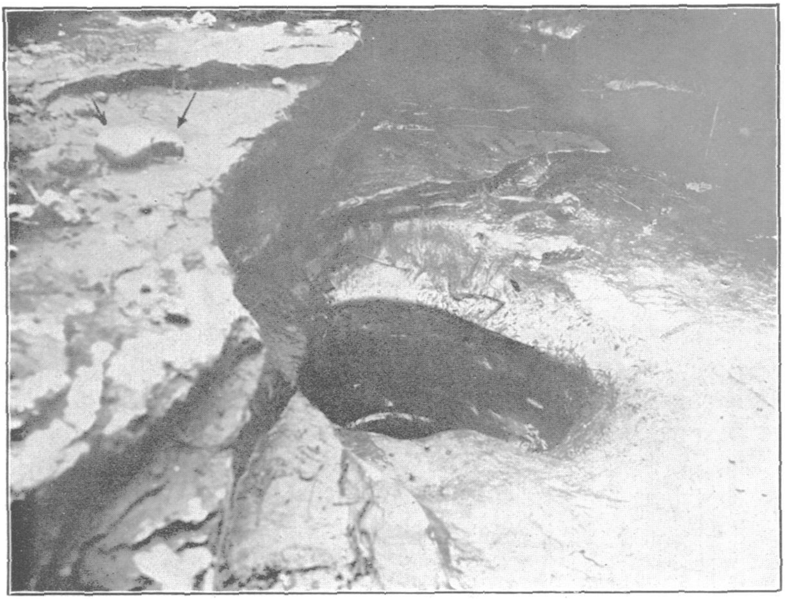

FIG. 10. ANOTHER NORMAL POTHOLE IN UPPER GORGE OF CASCADILLA CREEK, ITHACA, N. Y. Note the two rounded grinding stones removed from the hole.

Structural Phenomena of Bed Rock Leading to the Initiation of Normal Potholes.—It is immediately apparent that the primary factor in the initiation of a normal pothole development is the presence of some condition of the bedrock channel over which the stream flows that will give a rotary motion to the water. Evidently the chief, and perhaps the only condition that brings this about is the occurrence of some structural irregularity that leads to the development of a shallow depression in the stream course. The possibilities of this kind are quite numerous. There may be mentioned, *irregularity in* *bedding, ripple marks, lenticular concretionary structure, solution irregularities, and joint planes.*

Irregularity in bedding is of very common occurrence in stratified rocks and is well illustrated by Fig. 11. The rock surface, developed along stratification planes, is often very irregular and this condition frequently extends into the structure of the underlying material. As the stream erodes the general area of its channel bottom the tendency is to flake off such bedrock in accordance with its structural undulations. Thus a hummocky surface is created and in the shallow depressions between the knobs sediment tends to collect.

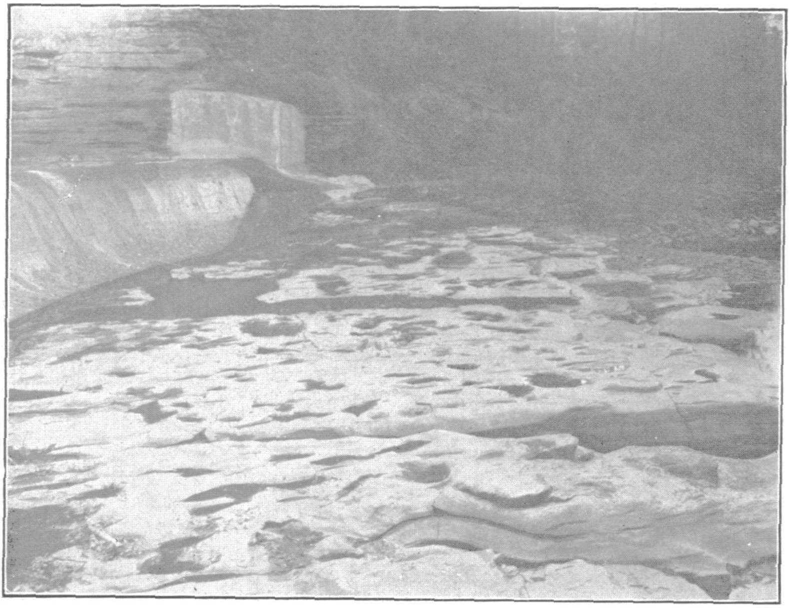

FIG. 11. IRREGULARITY IN BEDDING OCCURRING IN SIX MILE CREEK VALLEY, ITHACA, N. Y.

Ripple marks are familiar features in stratified rocks. Variations in their development are shown in Figs. 12 and 13. The troughs between the crests afford a favorable place for sediment to lodge.

Another special case of irregularity is due to what may be termed "*lenticular concretionary structure.*" This is found where beds containing concretions have been bowed up over the concretions and caused to sag beneath them, as is apparent in Fig. 14. No potholes have been observed in such a formation

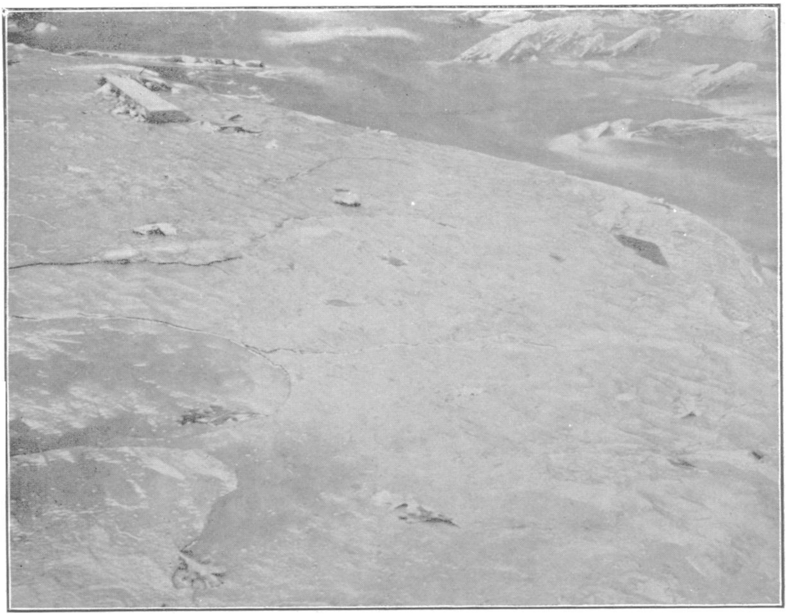

FIG. 12. RIPPLE MARKS IN SHALES IN BED OF FALL CREEK NEAR SIBLEY COLLEGE, ITHACA, N. Y.

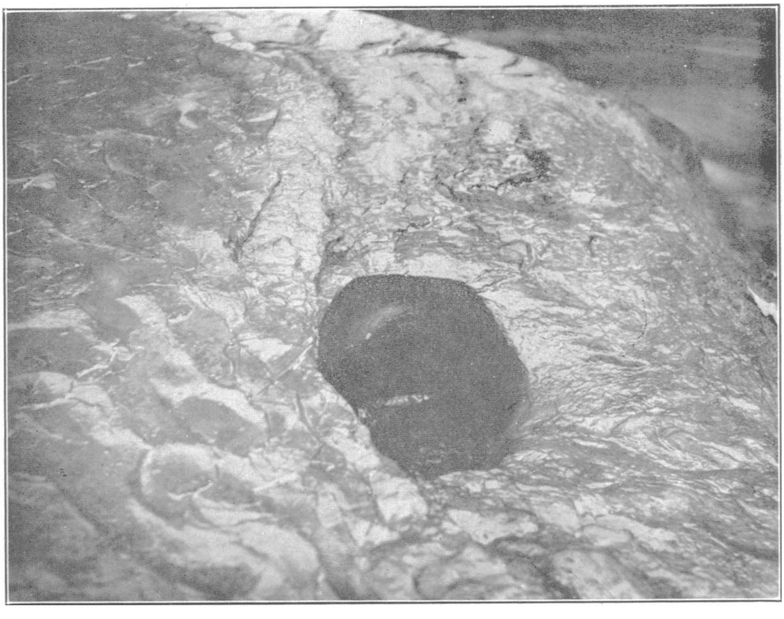

FIG. 13. POTHOLE IN SHALE. Surface shows rather irregular ripple marks, located near area shown in Fig. 12.

by the writer, but it is quite possible that such structure may cause the initiation of potholes in a manner somewhat similar to that in which it caused the initiation of Tide Pools as described by Henkel.[26] If one of the concretions should be removed by stream grinding it would leave a shallow depression that would act as a catch-all for the rock tools of the stream and a pothole might eventually develop. See Figs. 15 and 16.

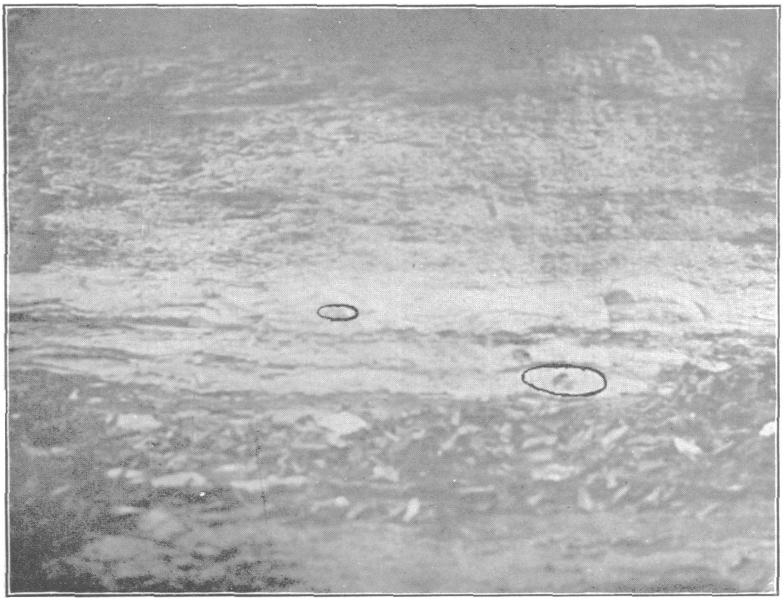

Fig. 14. Lenticular Concretionary Structure in Upper Gorge of Buttermilk Creek, near Ithaca, N. Y.

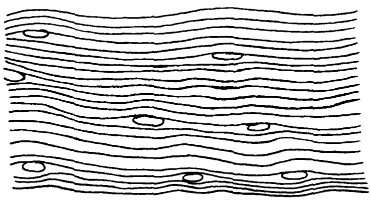

Fig. 15. Lenticular Concretionary Structure.

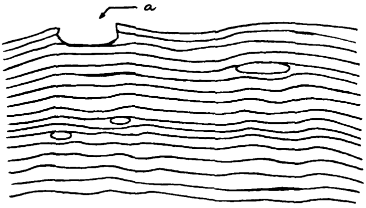

Fig. 16. Depression formed by the Removal of a Concretion.

Solution Irregularities.—These slight irregularities, illustrated by Fig. 17, are due primarily to the solvent action of the water and are especially common in limestone rocks and are often associated with potholes.

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[26] Henkel, Isabel, " A Study of Tide Pools on the West Coast of Vancouver Island." *Postelsia*—The Year Book of the Minnesota Seaside Station for 1906, pp. 298–303.

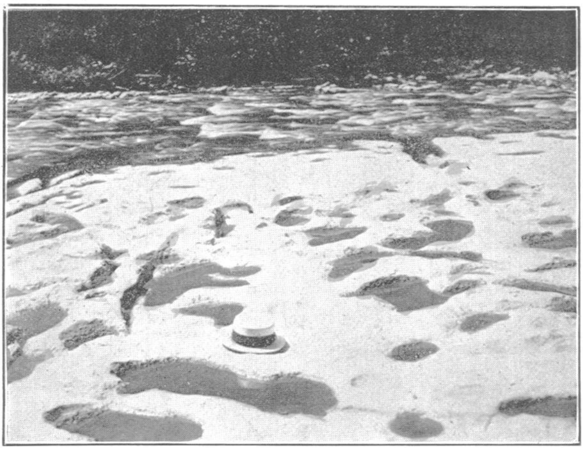

FIG. 17. SOLUTION IRREGULARITIES IN LIMESTONE, TAUGHANNOCK CREEK, NEAR ITHACA, N. Y.

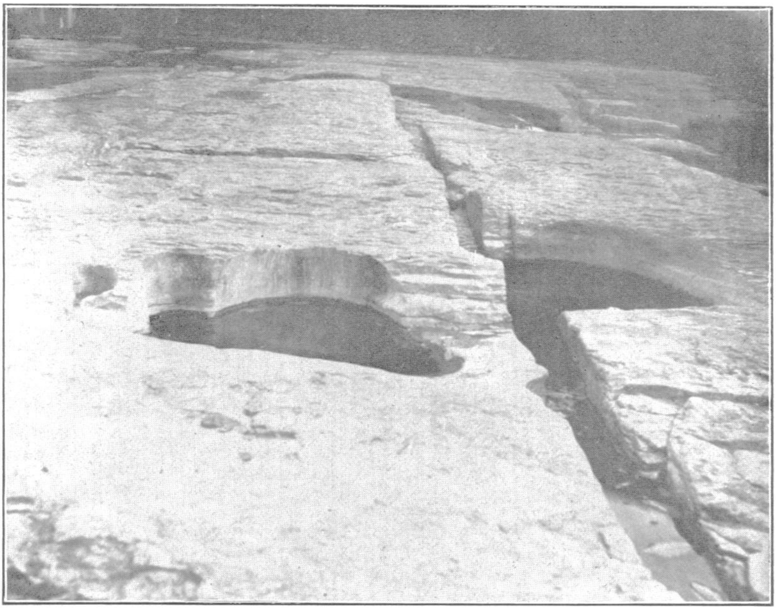

FIG. 18. JOINT PLANES WIDENED OUT BY EROSION AND POTHOLES OCCURRING ALONG THE JOINT PLANES, FALL CREEK, ITHACA, N. Y.

Joint planes seem to be the most important single factor in causing the initiation of the normal potholes. Along a single joint plane the rock is less resistant at some points than others.

This is notably the case in shales, where fragments may often be more readily detached in certain spots adjacent to the joint crevices than elsewhere. The resulting depression, if it is in the course of an eroding stream, frequently becomes enlarged. Again, at the point of intersection of planes, the corners of the rock are readily chipped away by boulders striking against them or such corners may be worn away by the combined processes of stream grinding (corrasion) and solution (corrosion). If the bed rock at the place of such intersection of joint planes is submerged only a part of the time and exposed during periods of low water, it is possible that weathering will also aid in enlarging the depression. Such hollows apparently afford most excellent sites for the development of potholes (see Figs. 18, 19 and 20).

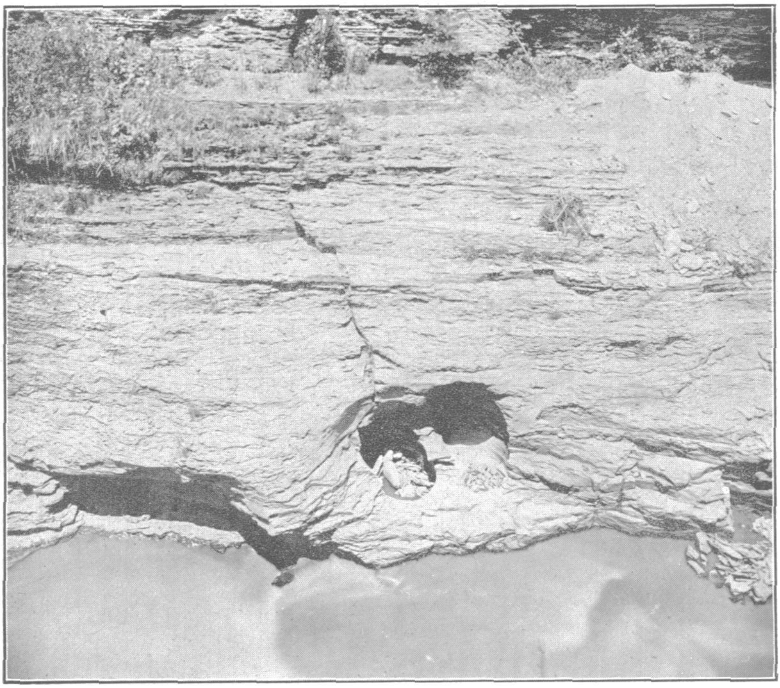

FIG. 19. POTHOLES DEVELOPED ALONG A JOINT PLANE, FALL CREEK, ITHACA, N. Y.

Joint planes, in addition to occasioning hollows at which potholes may start, may also influence the later development of the holes. The joints do not always extend vertically into the rocks. Sometimes they are inclined away from the perpendicular, or in geological terms, have a considerable *hade*. Assume, as shown in Fig. 21, that the joint plane extends vertically into the rock mass, *i. e.*, that the hade is 0°. If this joint plane cuts the edge of the hole or occurs near the hole, the line of weakness will be continued straight down and in accordance with these conditions, the pothole should theoretically be excavated vertically into the bedrock.

If, on the other hand (see Fig. 22), the joint plane has a large hade, the hole should, if our theory is correct, extend into the rock at an angle approximately equal to the hade, provided that the joint plane does form a line of weakness along which the effectiveness of erosion is concentrated. While no examples have been observed by the writer, where it was certain that such was the case, in several instances it seemed quite possible that hading of a joint plane had been a factor.

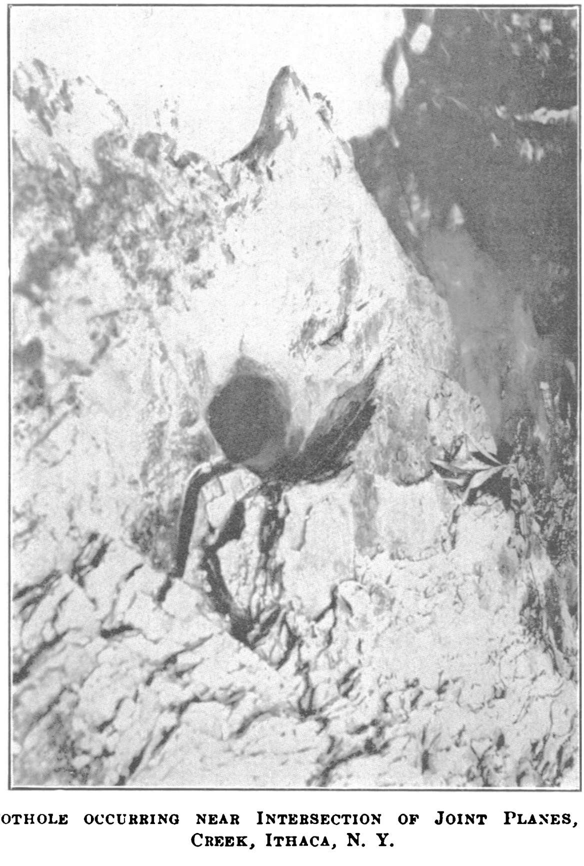

FIG. 20. POTHOLE OCCURRING NEAR INTERSECTION OF JOINT PLANES, CASCADILLA CREEK, ITHACA, N. Y.

Potholes Inherited from Preexisting Conditions.—As will be noted from the foregoing discussion, it is easy to conceive of various structural variations in the bedrock of stream courses, that might cause the initiation of potholes and influence their later development. To deduce on theoretic grounds the probable effect of these structural phenomena is not difficult. Yet, after examining many holes, it became apparent that the connection between their occurrence and such structural features was by no means so obvious as would at first seem probable. Particularly is this true of many of the larger, more typical, well-developed holes. Even when a detailed search was made it proved difficult to find single examples where incontestable correlations could be made between initiating cause and the occurrence.

There is obviously a connection between waterfalls and plunge pools. Furthermore, there is every gradation between plunge pools and normal potholes. The latter often mark the site of waterfalls the crest of which has since receded. Such potholes usually occur in a series leading up to the site of present active development. Excluding these, there still remain a number of potholes, the occurrence of which does not present evidence of formation by waterfalls and yet they seem unrelated to existing structural conditions. Perhaps no single one of a number of such holes will show any distinct relation to an initiating cause or reason for development at just that point. What then is the cause of these potholes? Why are they found at such places where no relation seems to exist between them and the structural phenomena present?

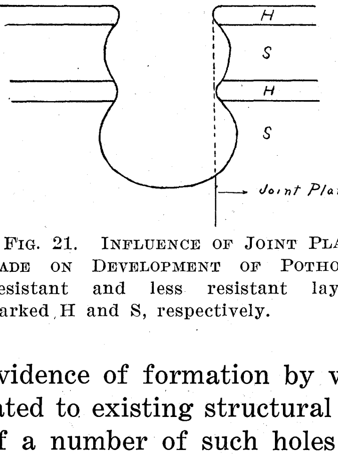

FIG. 21. INFLUENCE OF JOINT PLANE HADE ON DEVELOPMENT OF POTHOLE. Resistant and less resistant layers marked H and S, respectively.

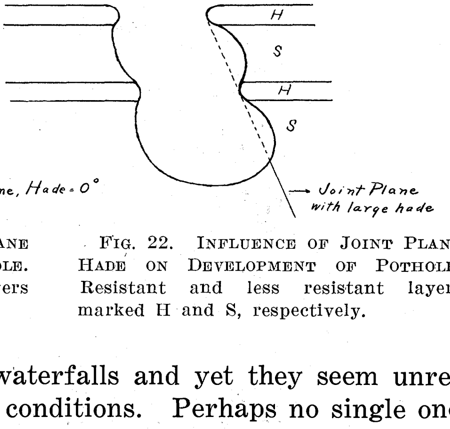

FIG. 22. INFLUENCE OF JOINT PLANE HADE ON DEVELOPMENT OF POTHOLE. Resistant and less resistant layers marked H and S, respectively.

It would seem that most normal potholes owe their existence to initiating causes that have disappeared since the formation of the holes. Accordingly it is proposed to describe them as *potholes inherited from preexisting conditions.*

The case may be especially well illustrated in connection with joint planes. Some of the joints are strong in sandstone and notably weak in underlying shales, according to Sheldon.[27] Assume that at an earlier stage in the downcutting by the stream a pothole was initiated in the sandstone layer due to the intersection of joint planes which were strong in the sandstone but weak in the shales beneath. Assume further that this hole attained a considerable depth and development and that its lower portion was cut into the shales in which the initiating joint planes did not continue. In time the stream erosion wore away the sandstone layer. The pothole, however, continued to be eroded in the shales. Once started, the swirl of the water currents continued to be effective and the hole was deepened at a rate commensurate or surpassing that of the general erosion of the stream bed. Thus it remained a feature of the stream course when the bed of the stream has been cut below the layer in which the hole was originally started.

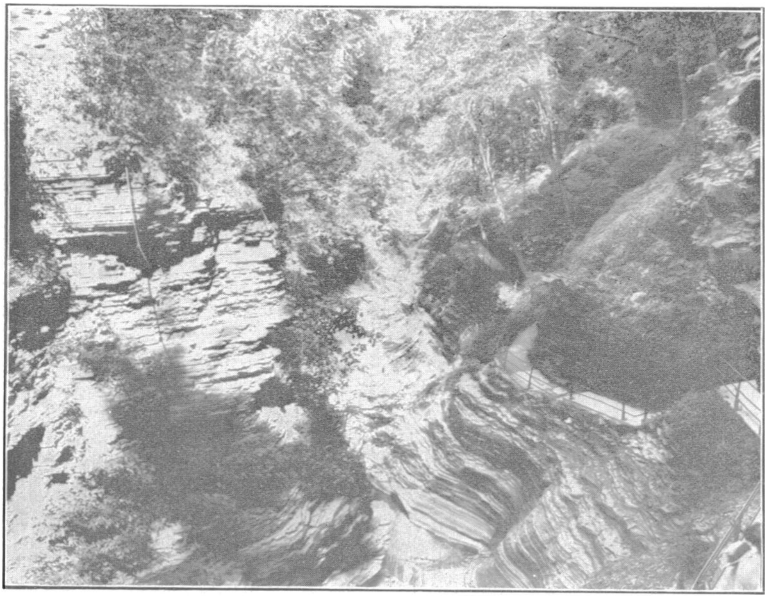

FIG. 23. SCALLOPED CHANNEL DUE TO POTHOLE ACTION IN WATKINS GLEN, N. Y.

Not only does this development history seem probable where the weak spots are caused by joint planes in the upper layers, but it also seems just as likely to occur if any one of the other structural weaknesses previously described occurs in layers later removed.

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[27] Sheldon, P. G., "Some Observations and Experiments on Joint Planes," *Jour of Geol.*, Vol. XX., No. 1, January–February, 1912, pp. 64, 65.

Henkel[28] observed in the case of tide-pools along the west coast of Vancouver Island, that some of the depressions were cut so that their bottom portions existed in sandstone and their top portions were in conglomerate, only a portion of the latter remaining due to erosion. Apparently this is an excellent example of inheritance from preexisting conditions.

The general theory, then, of inherited potholes accounts very satisfactorily for the development of large and small holes situated near each other in a rock surface which is apparently homogeneous throughout. The smaller holes are the most recently formed. They may in the future be extended downward into the underlying material. The material which is now at the surface may later be worn away and the potholes still continue their downward development (provided that conditions of erosion are maintained).

Irregularities of the Interiors of Potholes.—Where strata of unequal resistance to the grinding process of pothole formation occur within the depth of a single hole, the interior is commonly fluted, the resistant layer projecting beyond the weaker layers above and below. Possibly such fluting in some cases is due to variations in the erosive effectiveness of the currents moving in the hole, due to variations in the stream volume and its sediment load.

No conclusive determination of the exact conditions that lead to the progressive enlargement of the diameter of a pothole below the surface has been made. Brunhes and Brunhes[29] assert that centrifugal force causes the velocity of the water to increase at the sides of the hole, hence the tendency toward undercutting. There must also be a certain limiting depth to which a pothole can be excavated by a current of given volume and velocity provided with an optimum of rock tools. The variable factors, however, are so many that it would be difficult to establish any definite relations of this kind.

Pothole Development and Gorge Cutting.—It has been previously suggested that pothole development is a significant if not a primary process in the early stages of gorge cutting by streams. Fig. 2 illustrates this relation very clearly. Cleland[30] cites another instance of even more striking character. He describes a natural bridge formed in impure limestone over the Kicking Horse River, near Field, B. C., by the lateral enlargement and intersection below the surface of adjacent potholes. Some idea of the proportions of this feature may be gained by the figures he gives. The bridge averages ten feet in width, has a span of about eight feet and the arch is six to eight feet thick.

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[28] Henkel, Isabel, "A Study of Tide-Pools on the West Coast of Vancouver Island," *Postelsia*—The Year Book of the Minnesota Seaside Station for 1906, p. 293.

[29] Brunhes, B., and Brunhes, J., "Les Analogies des Tourbillons Atmospheriques et des Tourbillons des Cours d'Eau et la Question de la deviation des rivières vers la droite," *Anales de Geog.*, Vol. 13, 1904, pp. 1–20.

Watkins Glen, a quite famous gorge in central New York, owes much of its picturesqueness to the fact that its bottom course is almost exclusively the result of pothole erosion. The stream flows from one pothole to the next, forming the scalloped channel border illustrated by Fig. 23 as a result. Above, the gorge has been widened by weathering, but there is hardly any question but that these strata were also originally cut through by pothole grinding. In order to determine the rate at which potholes are enlarged, a plaster cast was made of a typical occurrence near Ithaca, N. Y., in the summer of 1914. Some time in the near future it is proposed to make another cast of the same hole and measure the volume of rock material that has been removed. At the same time it may be possible to determine how much the general level of the bed of the stream has been worn down. In this way it is hoped to obtain a suggestion of the quantitative relations of general and pothole deepening of stream channels. It would be interesting to have similar measurements made by observers in other localities as a comparison of results under different conditions would afford a basis for a general deduction of the effectiveness of the pothole grinding process in deepening stream valleys.

SUMMARY

1. Potholes develop only in streams that are actively eroding in fairly well consolidated rock.

2. An initial hollow in the bedrock is necessary to permit of the primary collection of the sediment and stones that are to be the tools with which the pothole is ground out.

3. The stream must carry at least a *moderate* amount of material to be used as grinding tools. Streams heavily laden with sediment tend to deposit rather than erode and too much material chokes the initial depressions.

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[30] Cleland, H. F., "North American Natural Bridges," *Bull. Geol. Soc. of America*, Vol. 21, 1910, pp. 321–322.

4. The initial hollow may be originated by any one of the following factors: irregularity in bedding; ripple marks; lenticular concretionary structure; solution irregularities; joint planes.

5. The inception of a given pothole may be due to one or more of these structural weaknesses.

6. The larger holes seem almost invariably to be *inherited from preexisting conditions.*

7. The later development of a hole is influenced by the following factors, among others: the volume and velocity of the stream; the direction of currents; nature, structure and position of the rock, the hade of joint planes; union of two or more holes.

8. Most of the erosion of the holes is apparently accomplished during flood stages.